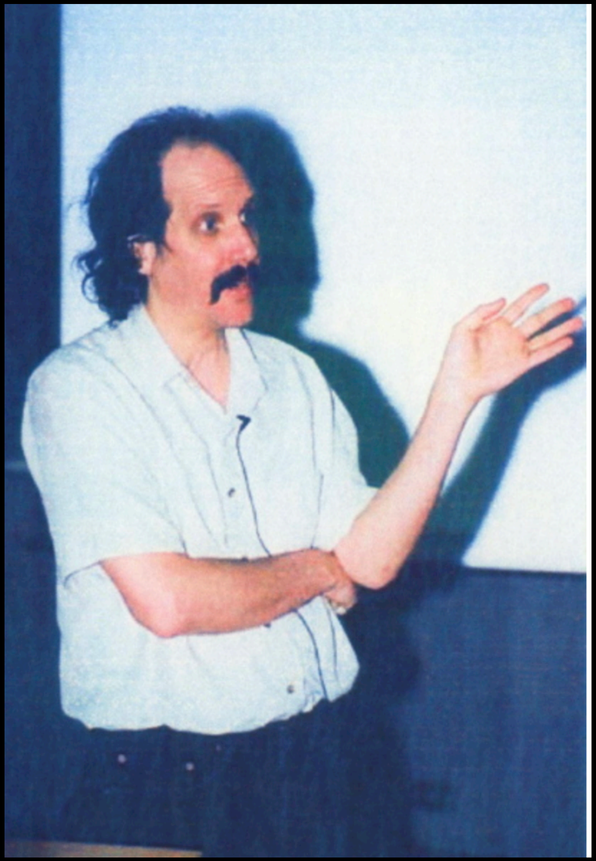
the limits of cosmology



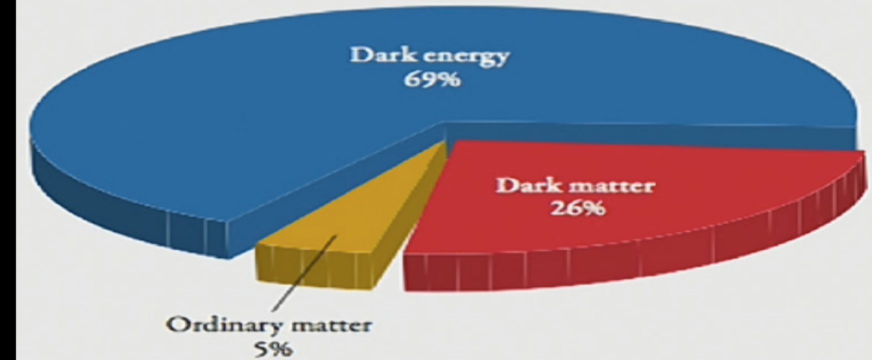
OLIVEFEST

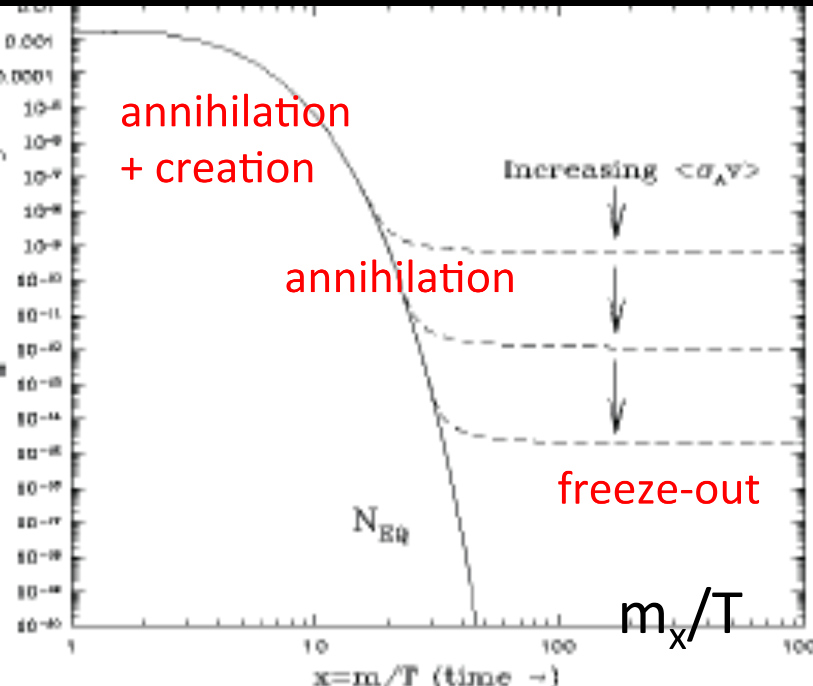
17 may 2017

Joseph Silk

IAP/JHU

What is the matter?



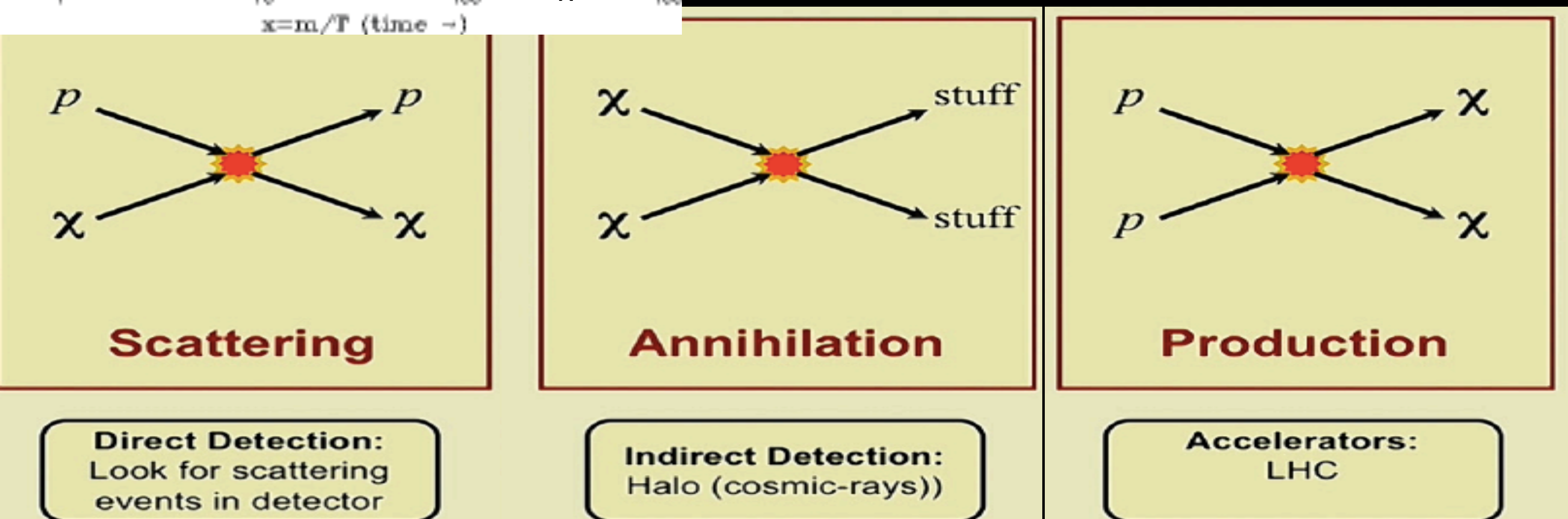


A beautiful theory

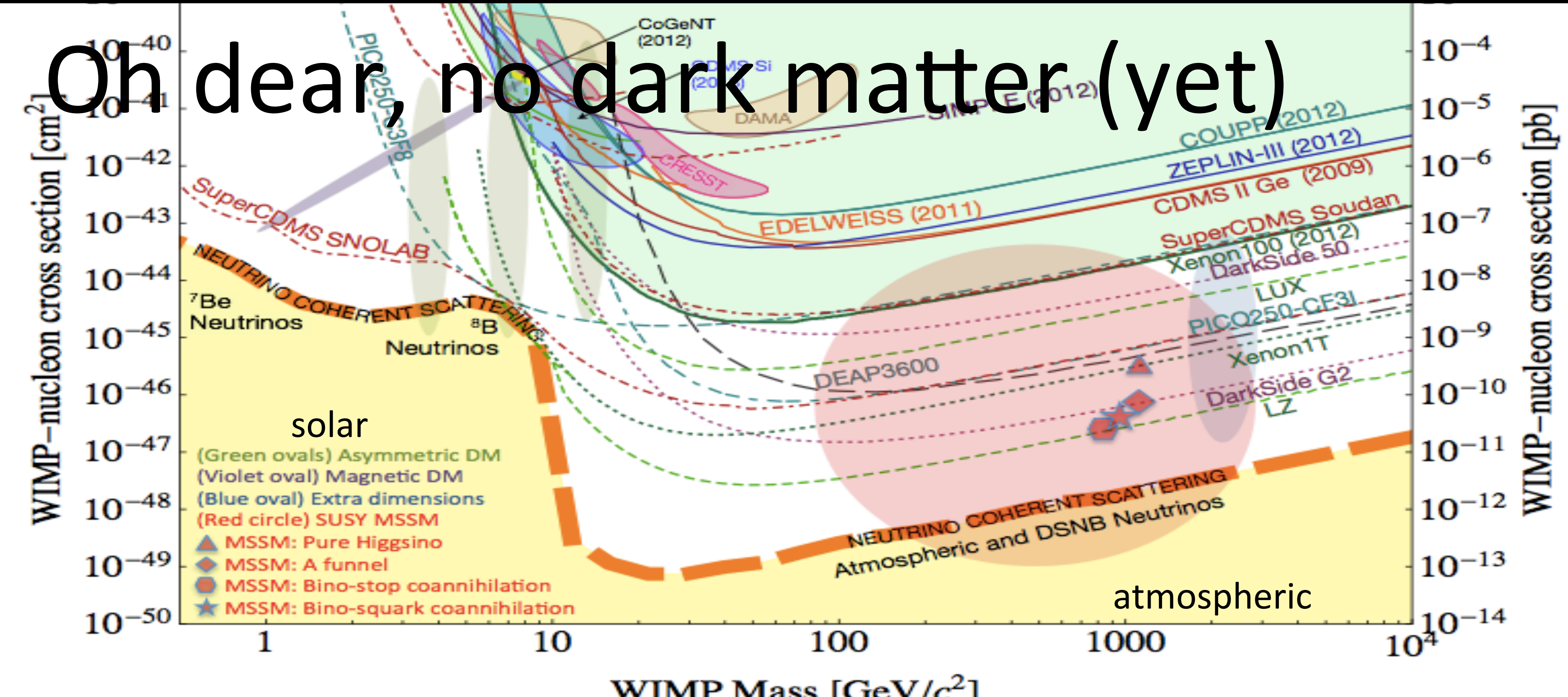
SUSY WIMP thermal freeze-out at $T\sim0.1m_x$

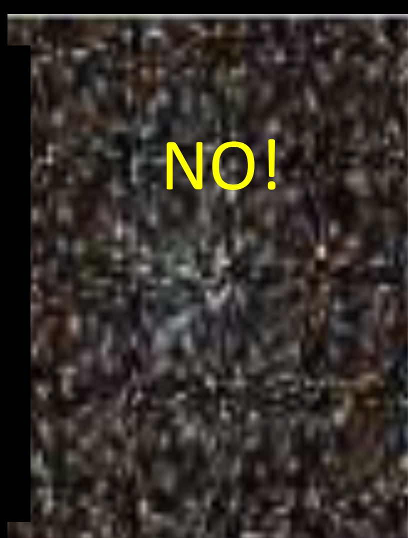
when $n<\sigma_{ann}v> \sim t_{exp}^{-1}$

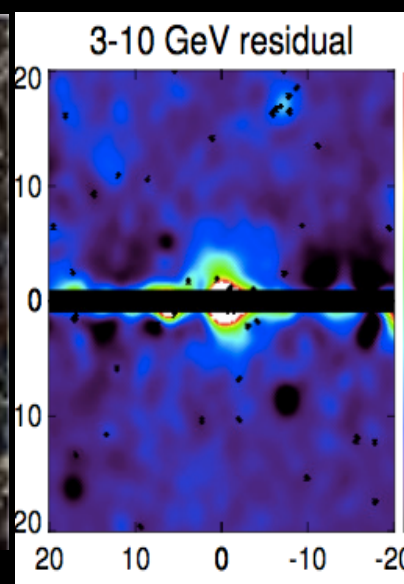
relic abundance $<\sigma_{ann}v>\sim3\mathrm{x}10^{-26}\ \mathrm{cm}^3/\mathrm{s} \sim0.23/\Omega_x$

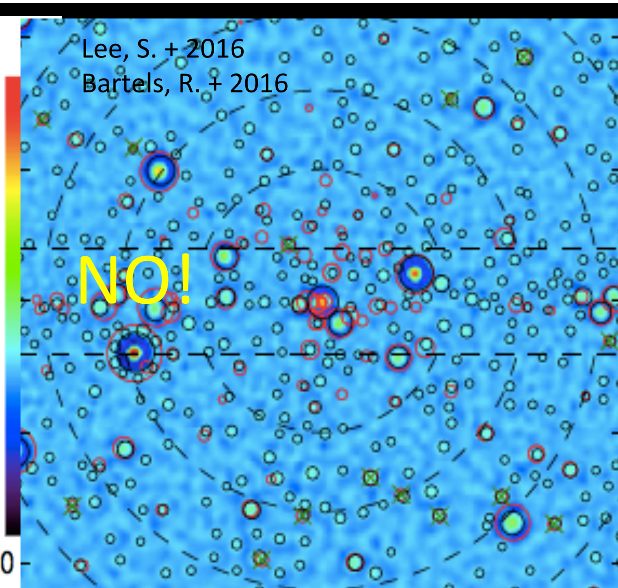


Oh dear, no dark matter (yet)









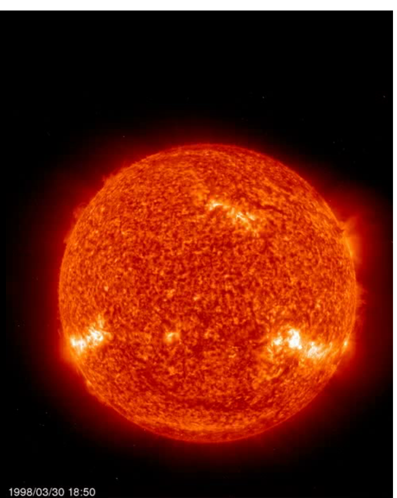
The Photino, the Sun, and High-Energy Neutrinos

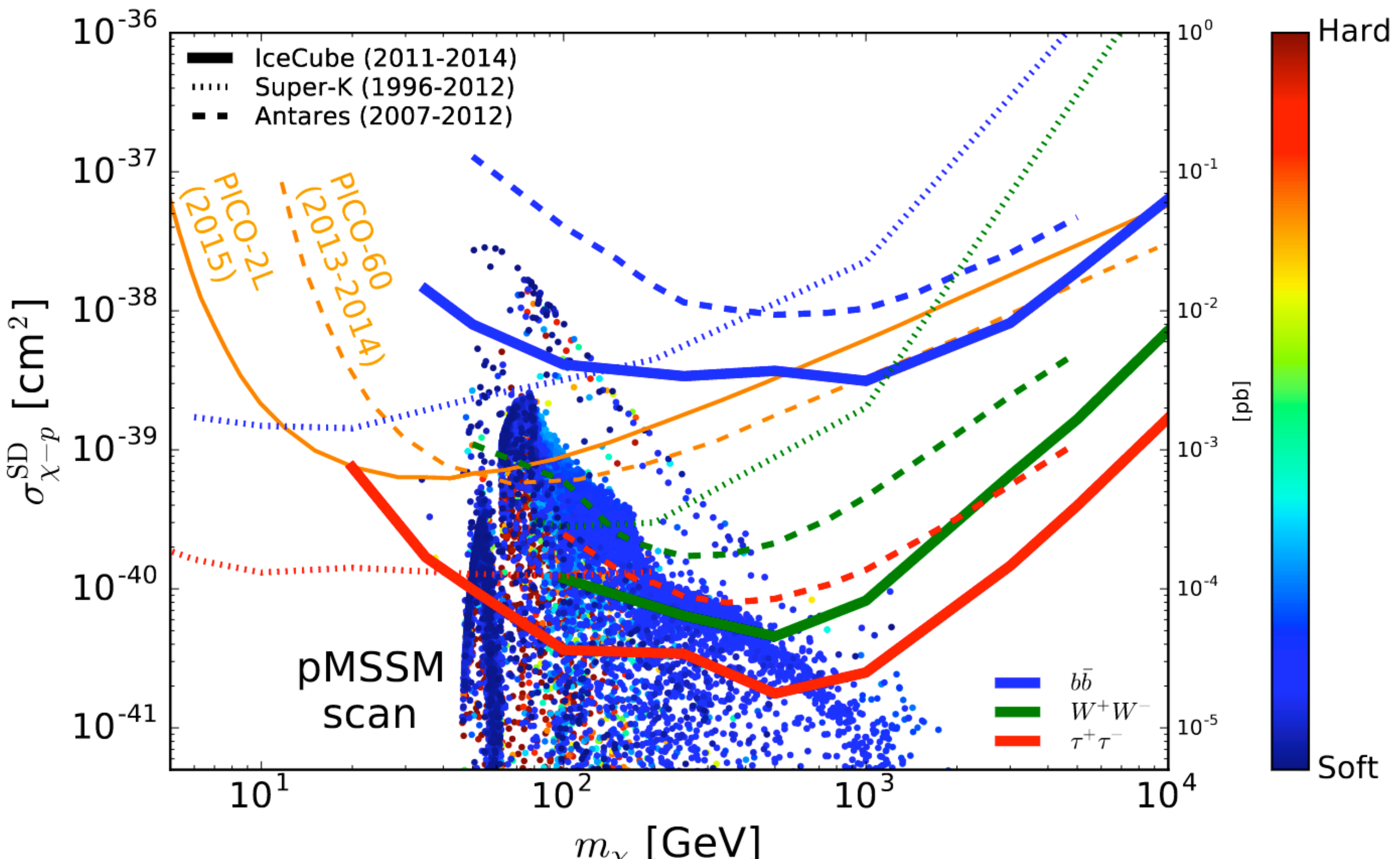
Joseph Silk
Department of Astronomy, University of California, Berkeley, California 94720

and

Keith Olive
Theoretical Astrophysics Group, Fermi National Accelerator Laboratory, Batavia, Illinois 60510

If the Univ
the dark mat
in the solar
neutrino-ind





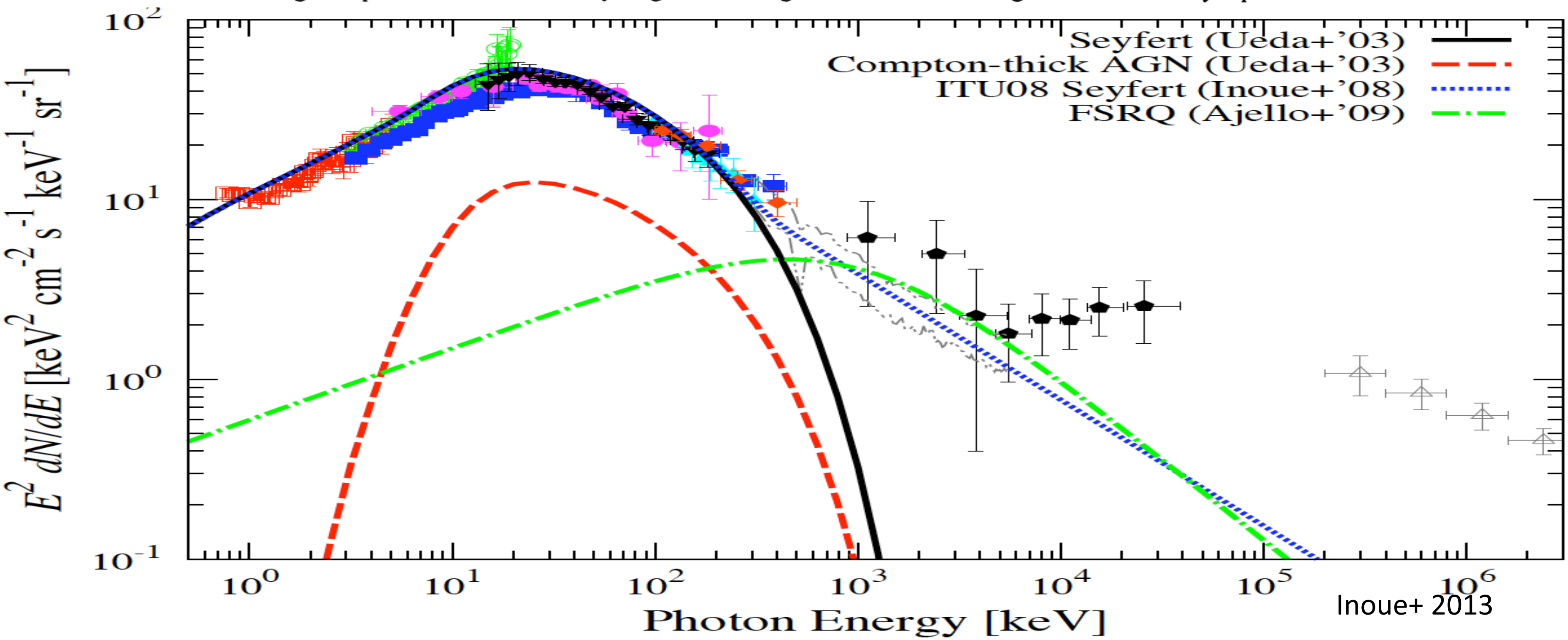
Diffuse Cosmic Gamma-Ray Background as a Probe of Cosmological Gravitino Regeneration and Decay

Keith A. Olive
Astrophysics Theory Group, Fermilab, Batavia, Illinois 60510

and

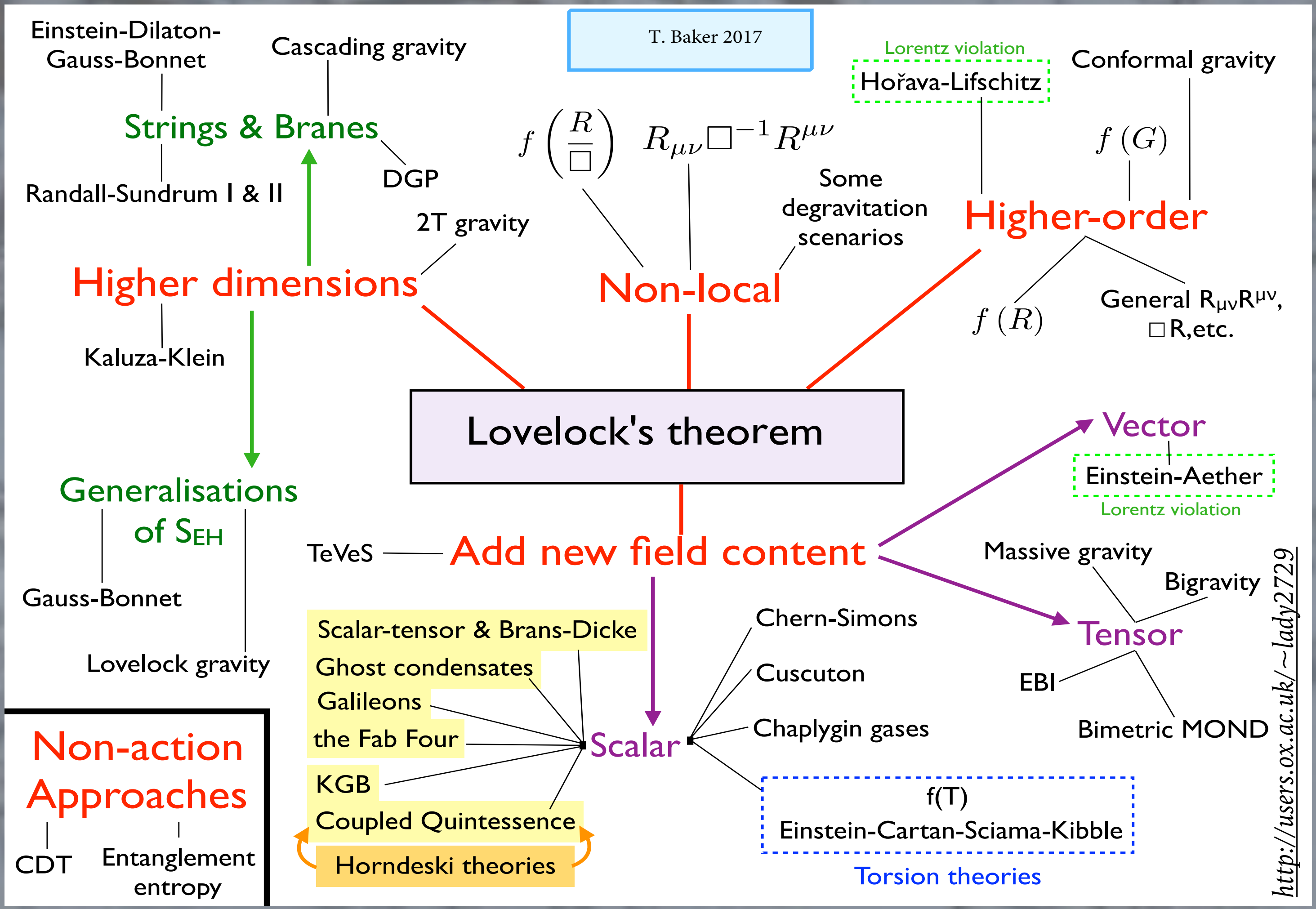
Joseph Silk
Department of Astronomy, University of California, Berkeley, California 94720
(Received 22 March 1985)

We predict the presence of a spectral feature in the isotropic cosmic gamma-ray background associated with gravitino decays at high red shifts. With a gravitino abundance that falls in the relatively narrow range expected for thermally regenerated gravitinos following an inflationary epoch in the

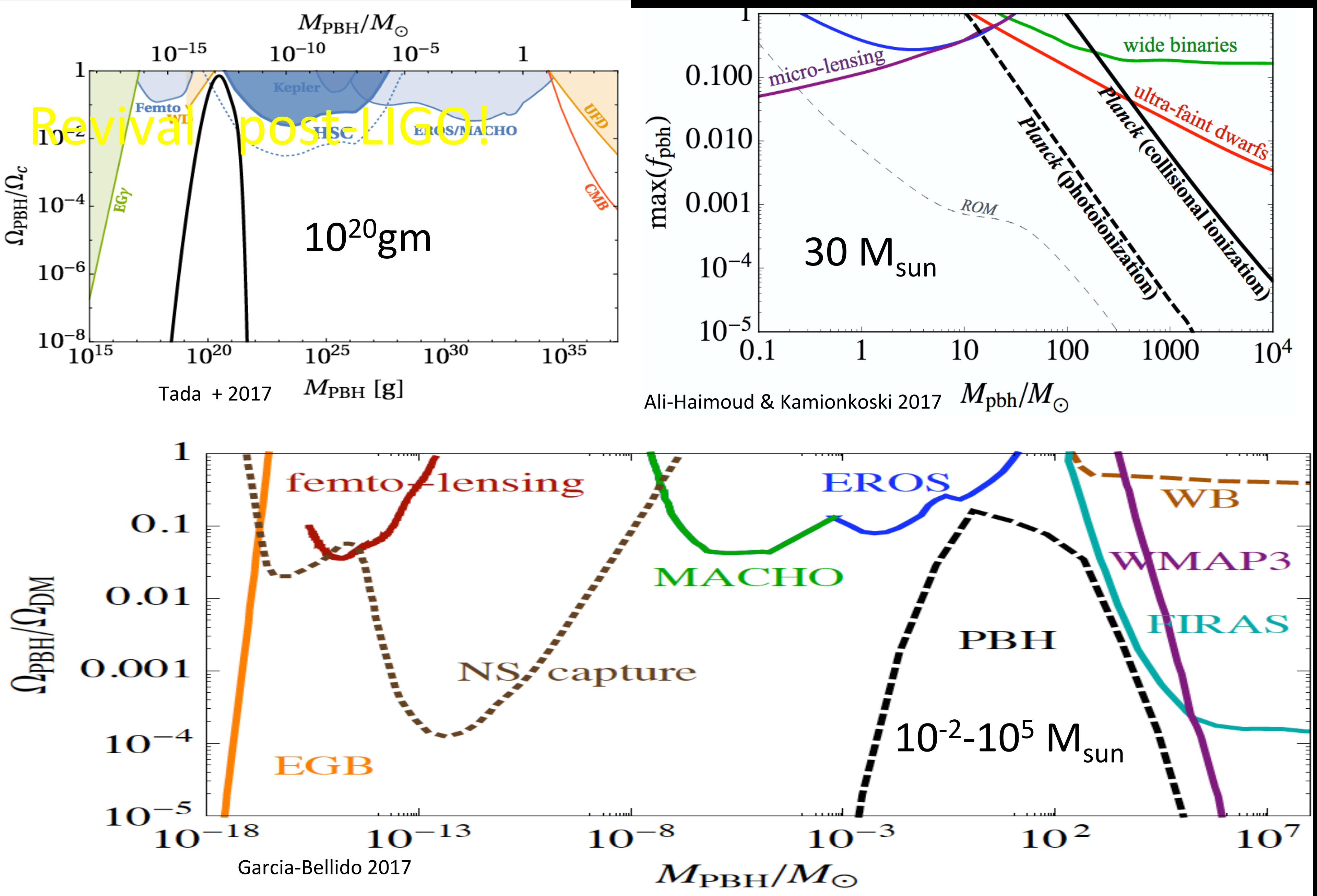


Lets look elsewhere

modifying gravity is ugly and doesn't work anyway

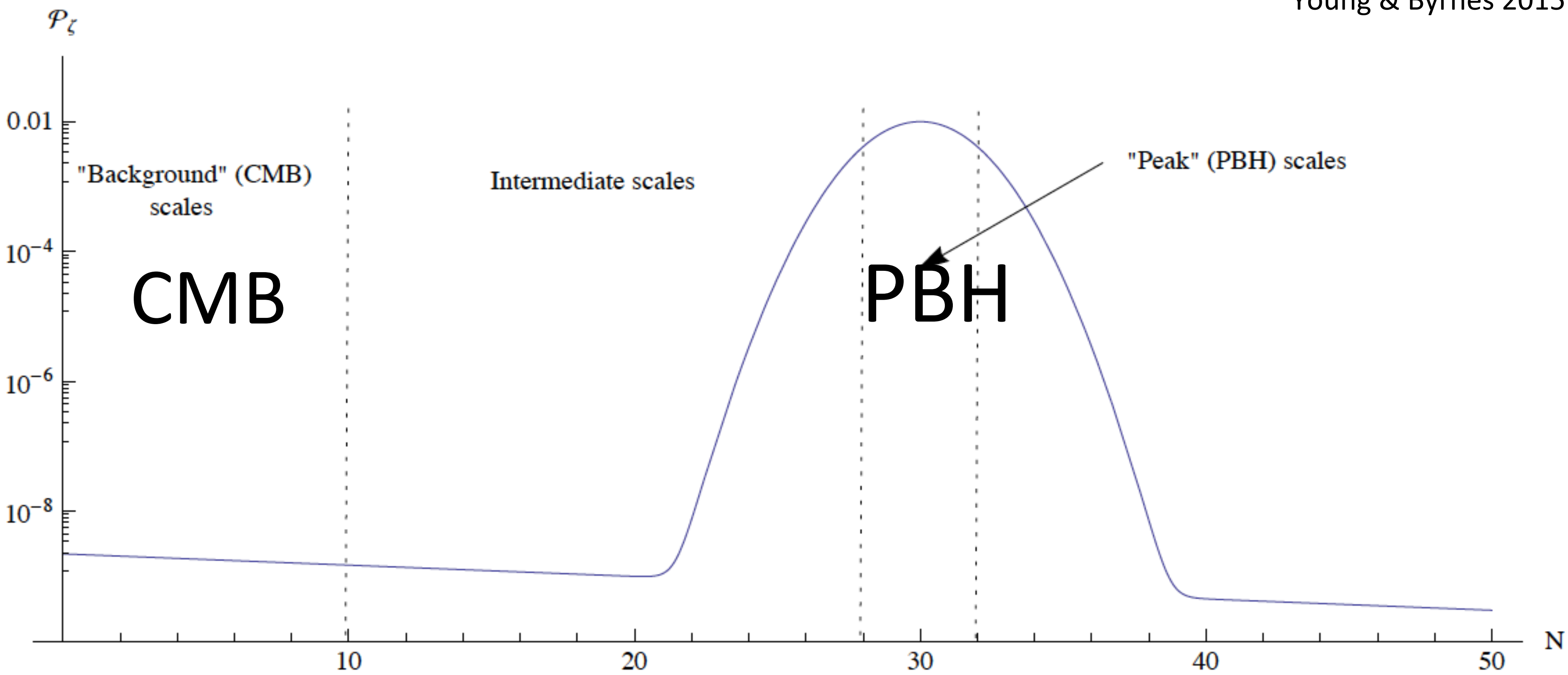


Primordial black holes as dark matter



PBH production by isocurvature modes: exponentially sensitive to theshold & biased

Young & Byrnes 2015



dwarf galaxy problems

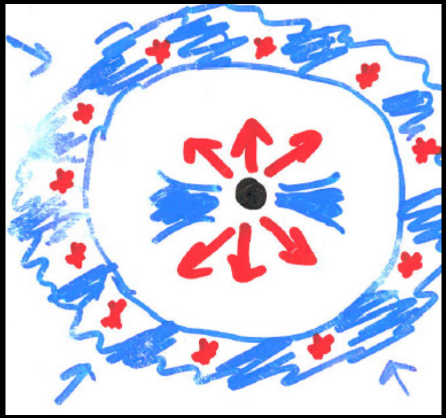
something new is needed: exotic DM?

- 1. number, cores vs cusps
- 2. Seeds for SMBH at high z
- 3. the "too big to fail" problem
- 4. ultrafaint dwarfs
- 5. reduced baryon fraction

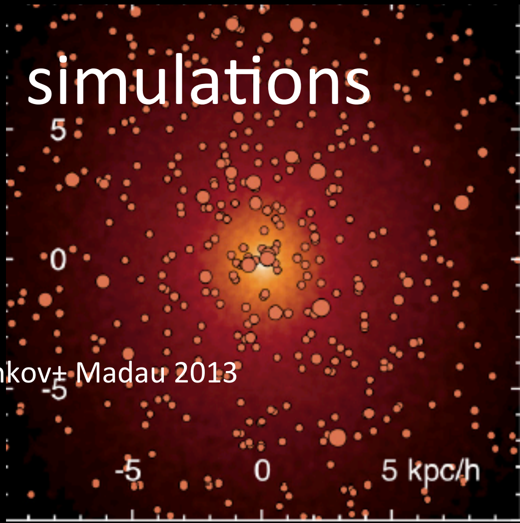
Occupation fraction of xr AGN in dwarfs ~ 1%

Baldassare 2015

baryonic feedback?



massive black holes



Rashkov+ Madau 2013

MBH ejected from dwarfs in mergers?

may need primordial BH!

The dwarf saga continues…

Why invent exotic dark matter?

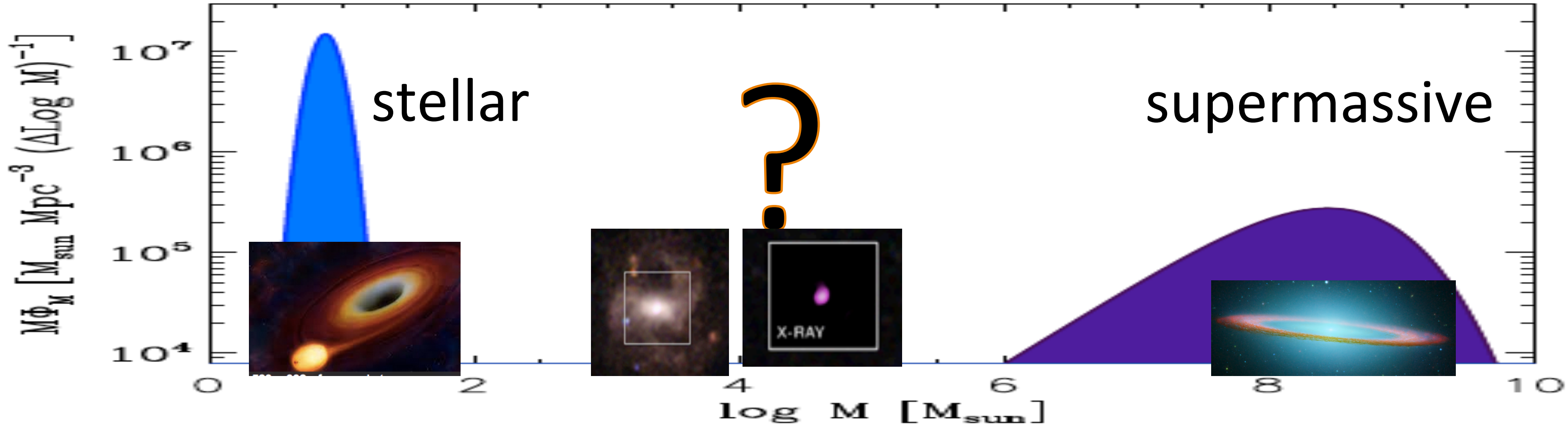
which can't solve all the problems anyway…

many papers on warm, fuzzy, self-interacting……

black hole feedback can do it all!

just baryons + known physics

works in principle…. devil is in the details

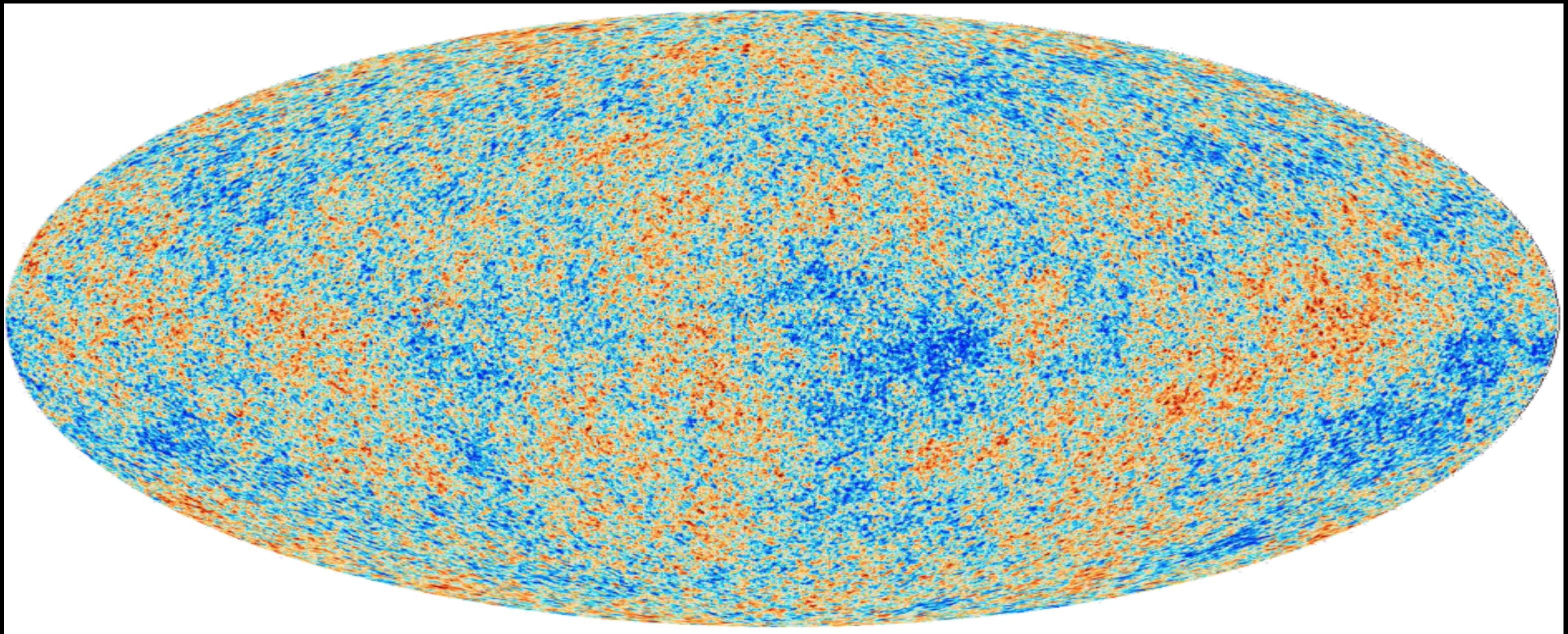


Where next in cosmology

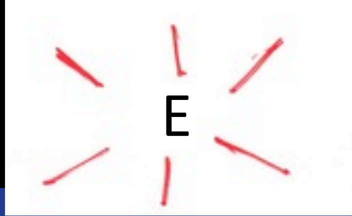
- Dark energy? no prediction for $w \neq -1$

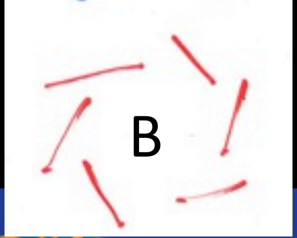
- Probing inflation via CMB polarization?

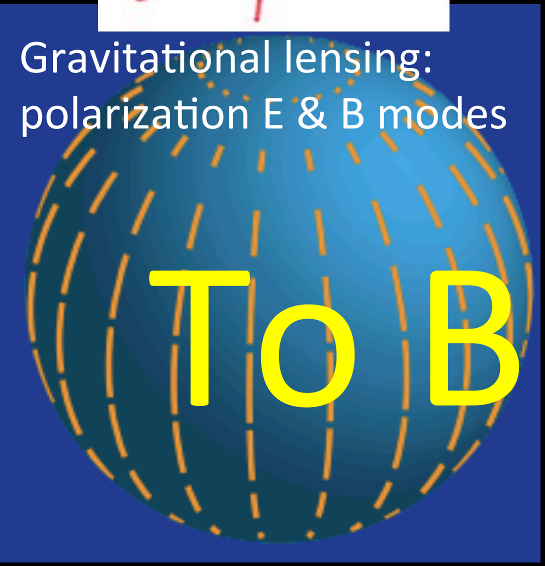
  no lower bound!



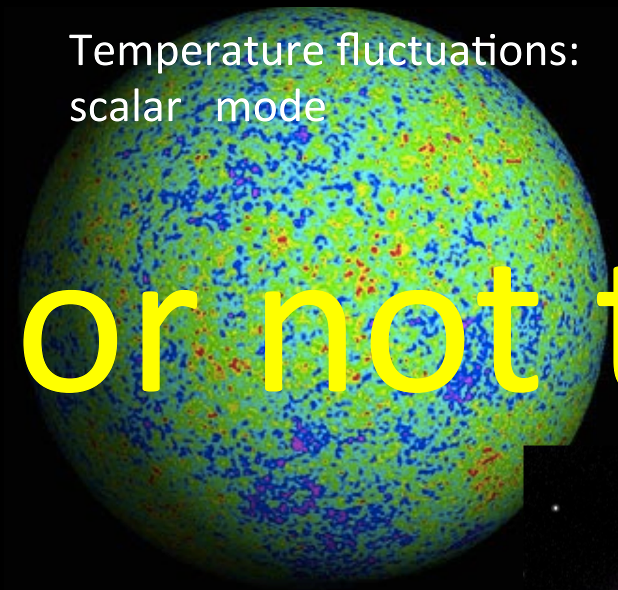
CMB



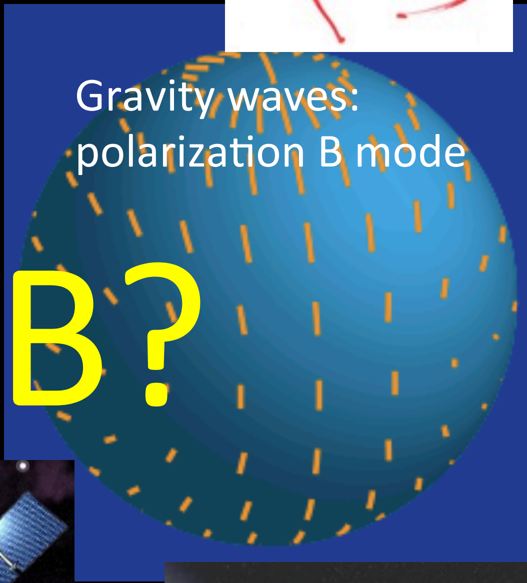




Gravitational lensing:
polarization E & B modes

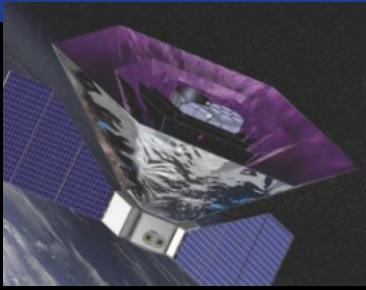


Temperature fluctuations:
scalar mode



Gravity waves:
polarization B mode

To B or not to B?



Satellites: LiteBIRD (JAXA launch in 2027?)

PIXIE (NASA launch in 2023?)

ground/balloon: CMB-S4, c. 2020

But there is no guarantee of a signal!

Another direction in cosmology

- inflationary is generically non-gaussian:
  $\delta T/T\,(1+ f_{NL}\,\delta T/T)$

$f_{nl} \sim\ n_s-1\ \ \sim 0.03$ with Planck $n_s=0.965$ Maldacena 2003

quadratic correction to potential in vanilla inflation

PBH require large scale-dependent non-gaussianity on scales much smaller than probed by CMB or LSS

ULTIMATE PROBE OF INFLATION

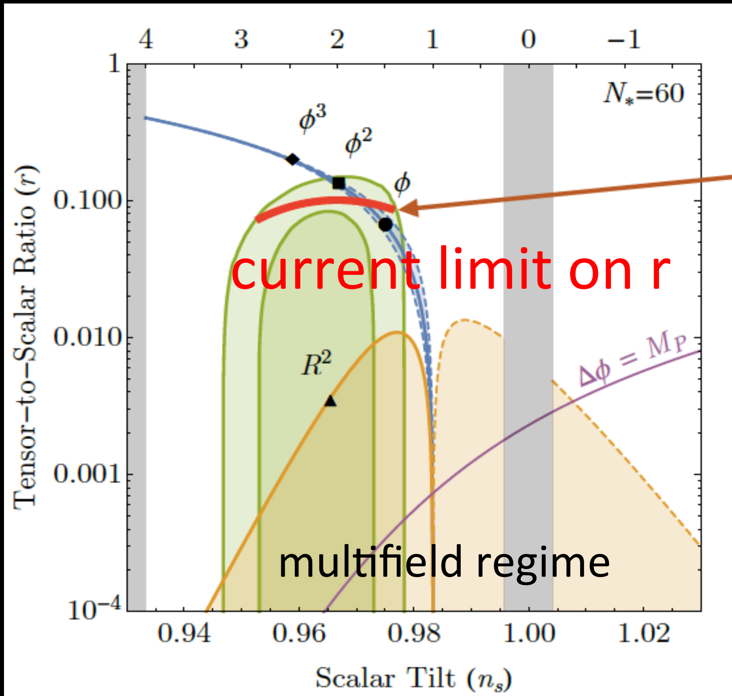
Only robust prediction of inflation is non-gaussianity.

signal is a small fraction $f_{nl}\,\delta T/T \sim 10^{-4} f_{nl}$ of temperature fluctuations

$f_{nl} < 10$ (current limit) vs ~1 (multifield prediction)

simple inflation already is strongly constrained by failure to detect imprint of gravitational waves in CMB

Planck-preferred inflation: $f_{nl} > 0.03$

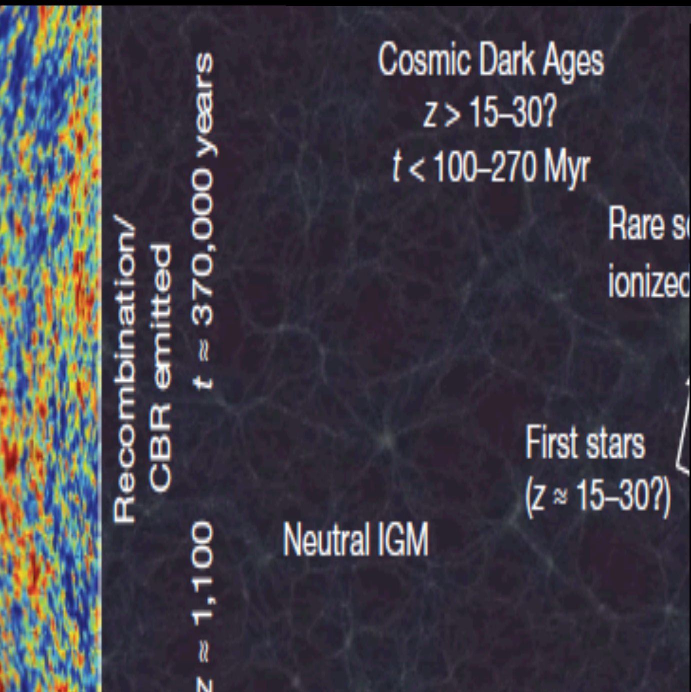


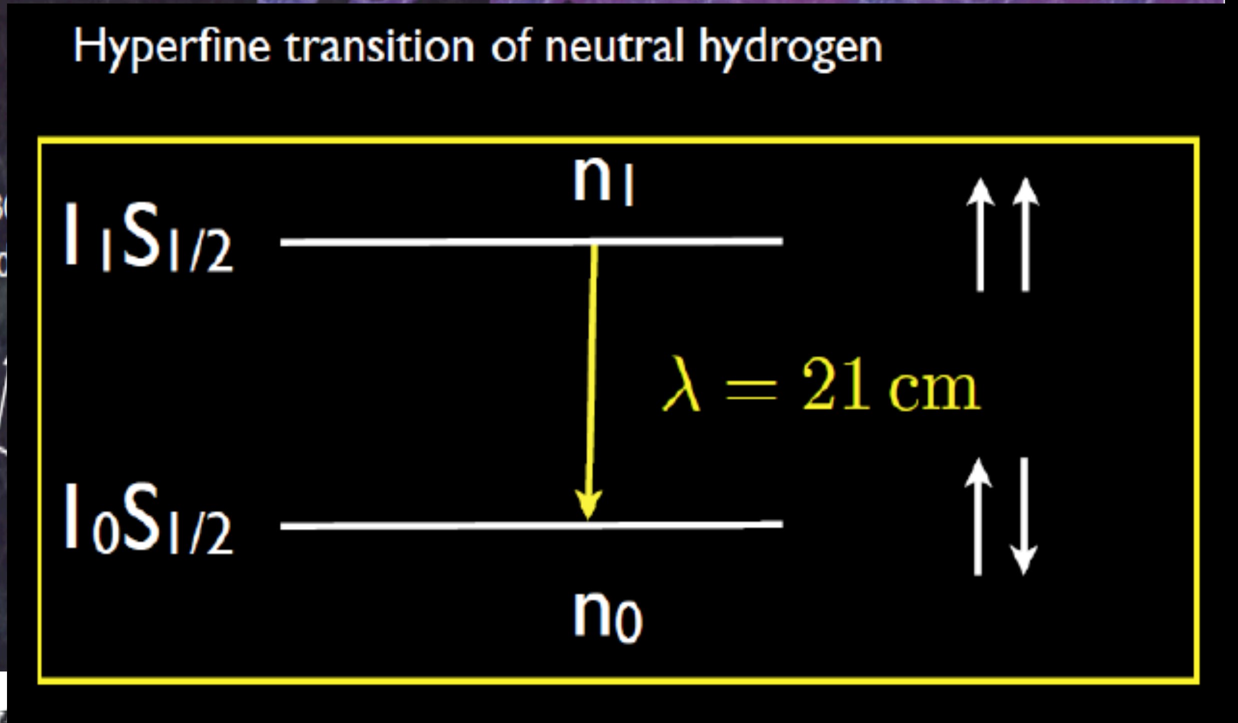
Can we improve on Planck by 10 or more?

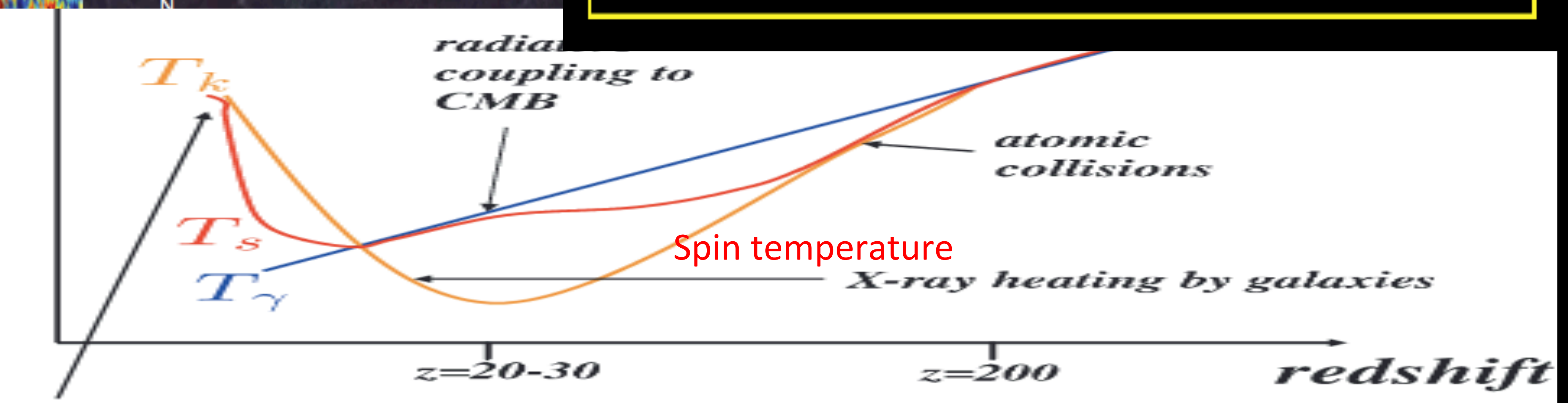
test inflation and at small scales probe PBH

THE DARK AGES OF THE UNIVERSE

$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\ \mathrm{Hz}$$

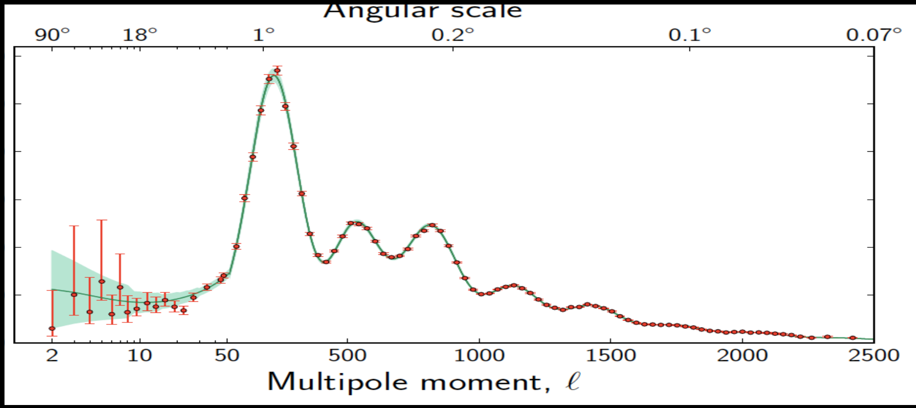




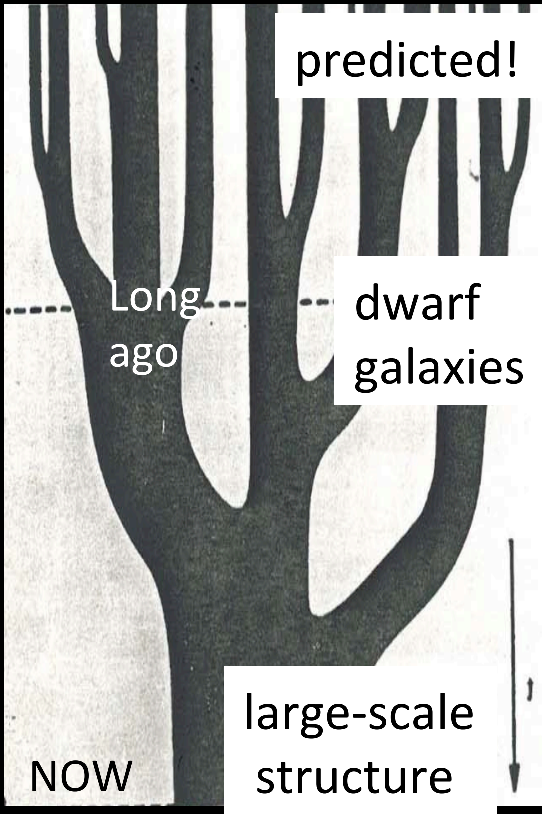


Microwave background probes $N \sim 10^6$ independent samples to $l \sim 1000$

limiting 2d accuracy $N^{-1/2} \sim 0.1\%$



How do we increase N ?



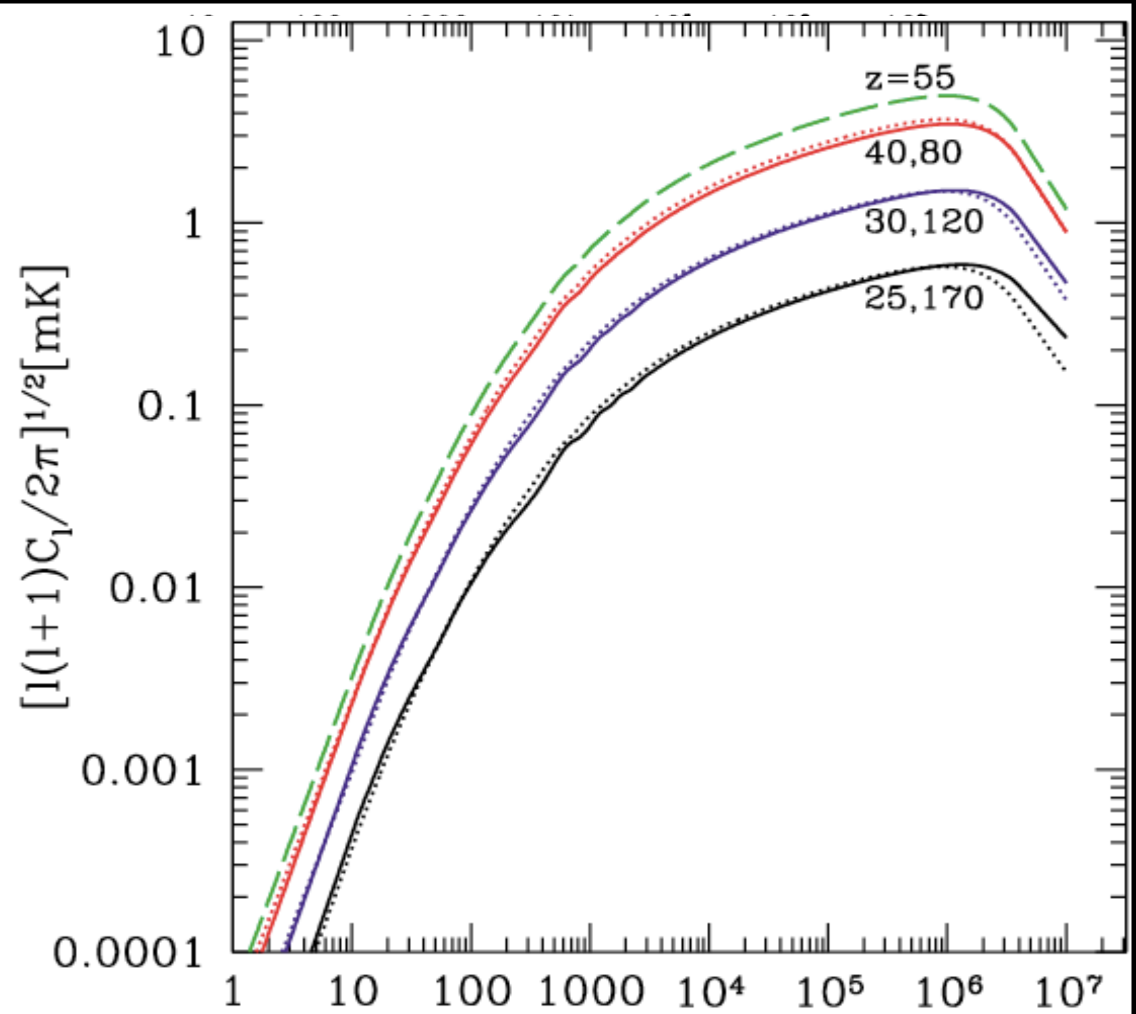
galaxy surveys? 3D probe

allow $N \sim 10^9$ but galaxies are biased probes

Need to go back to the dark ages and use gas clouds, the building blocks of galaxies.

This allows $N >> 10^{10}$

Power spectrum: CMB vs 21cm



Loeb & Zaldarriaga 2003

CMB has only $\ell \sim 10^3$ or $\sim 10^6$ modes

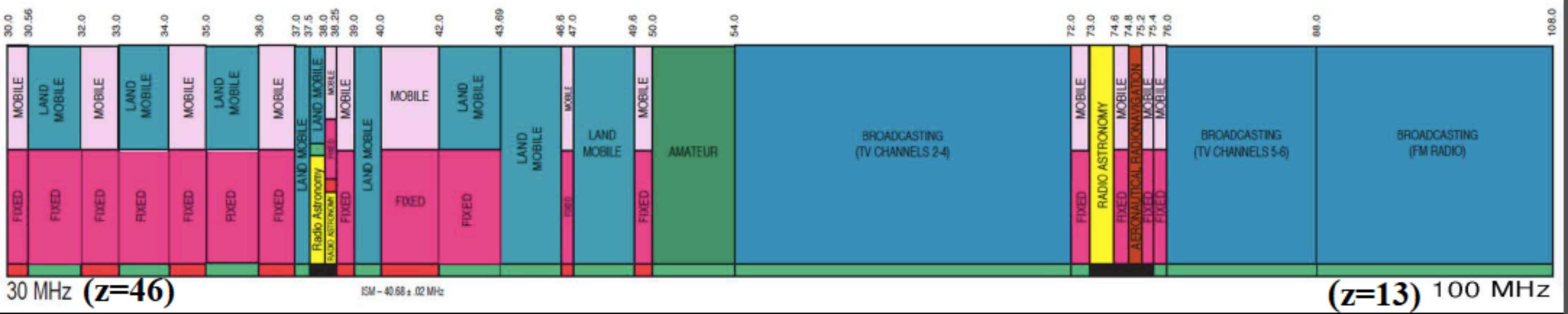
$f_{nl}\delta\phi > 1/\sqrt{N} \sim 10^{-3}$

Many more modes at 21cm

Sweet spot at z ~ 50 or 30 MHz

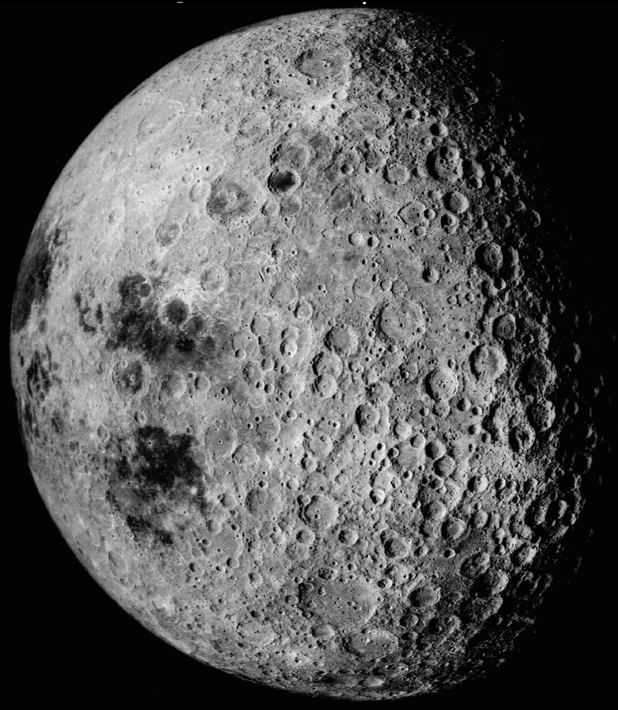
$f_{nl}\delta\phi \sim (n_s-1)\,\delta\phi \sim 10^{-6}$ requires $N \sim 10^{12}$ modes (or a few arc-sec resolution)

can slice sky in 3D: eg $\Delta\nu \sim 0.1$ MHz at $\ell \sim 10^5$ for $N \sim 10^{10} \times 10^2$



30-50 MHz is a very difficult frequency range to map from the Earth

Need to go to far side of MOON for low radio interference



Most radio-quiet environment in inner solar system

21 cm astronomy in dark ages

Optimal bandwidth L=1 Mpc ($\Delta\nu$/0.1MHz) slices of the universe

Need to resolve ($\ell \sim 10^5$) a few arc-seconds at wavelength of 10m

seek ~10mK signal for bright sky foreground: T_B~1000K

Optimal telescope array size is $\ell\lambda/2\pi$ or D ~100 km at $\lambda \sim$ 10 m

Sensitivity: need millions of dipoles for weak signal: $\frac{D^2}{4\lambda^2} \sim 10^7$

Allows N ~ 10^{10} patches on sky x 10^2 via tomography
to attain 10^{12} modes versus 10^6 in CMB

Not easy: need to remove non-gaussian foregrounds at level of x10^5

gain up to ~10^3 in $N^{1/2}$

CHIME: the world's most powerful radio telescope in British Columbia

10^{15} multiplies/sec for 1024 antennae at 400 MHz in 2017

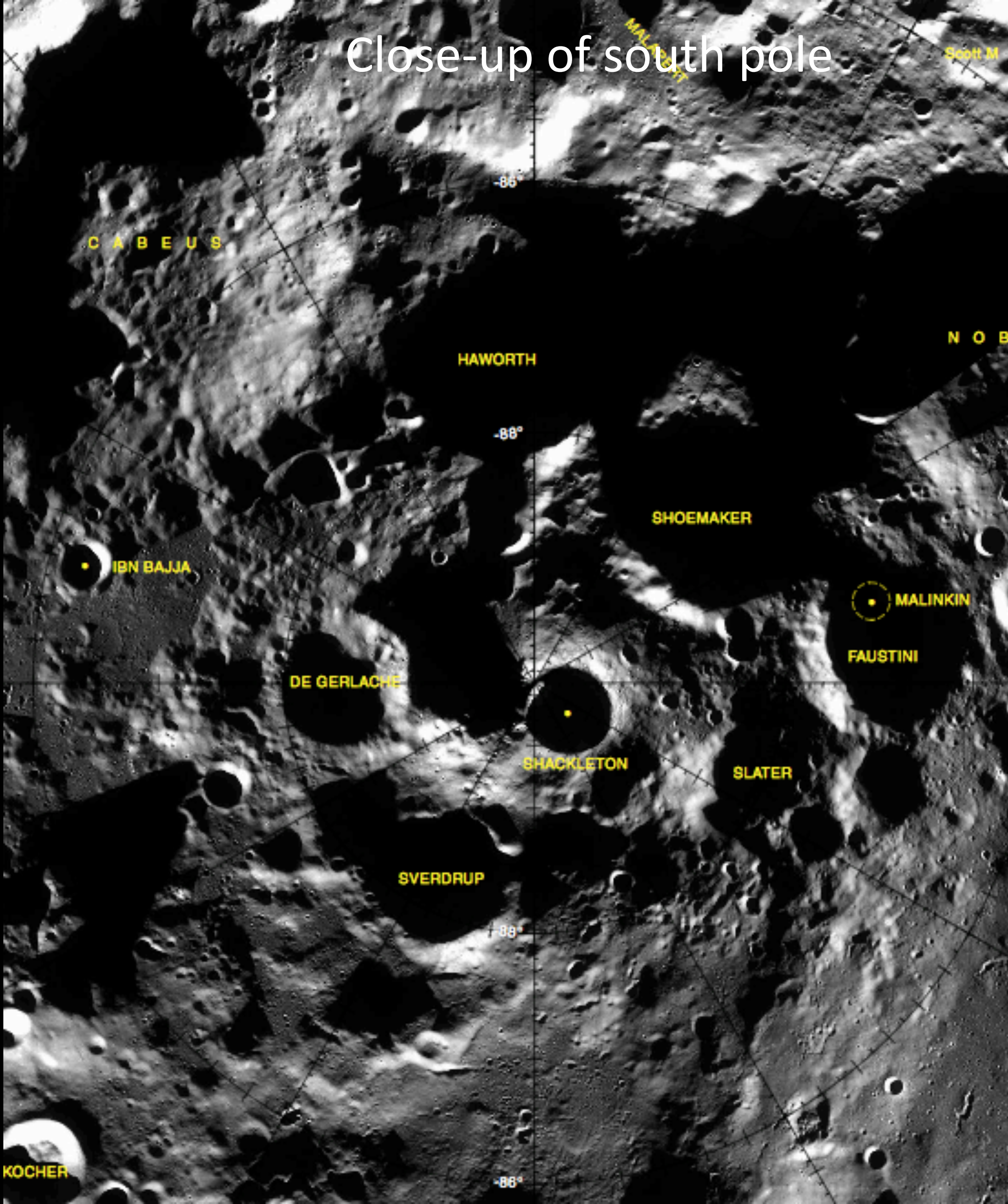
LUNAR RADIO ARRAY: 10^{20} multiplies/sec for 10^6 antennae at 30 MHz

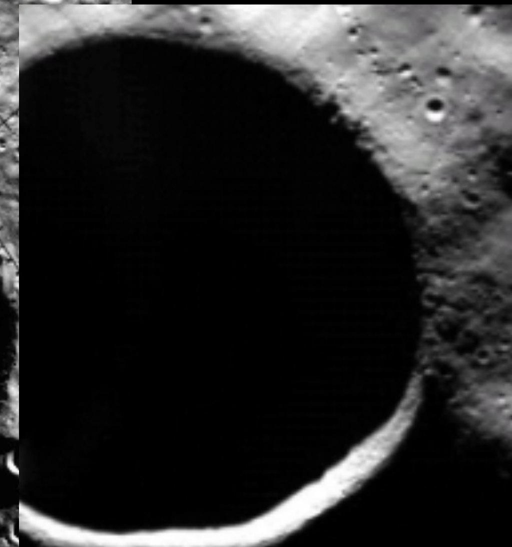
computing power achievable in 15 years from now?

Far side of the Moon ~ 2040

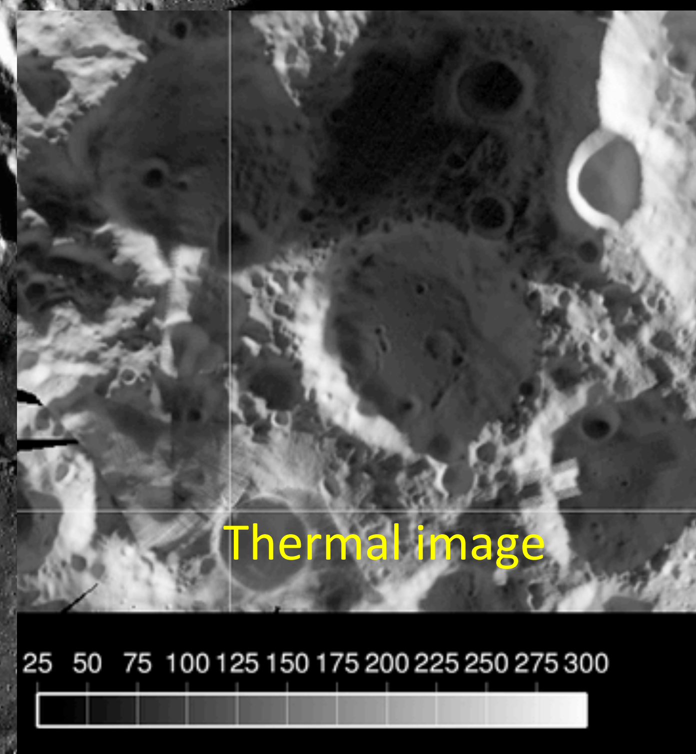
The ultimate dark ages explorer: a lunar dipole array with > 10^6 dipoles

Close-up of south pole



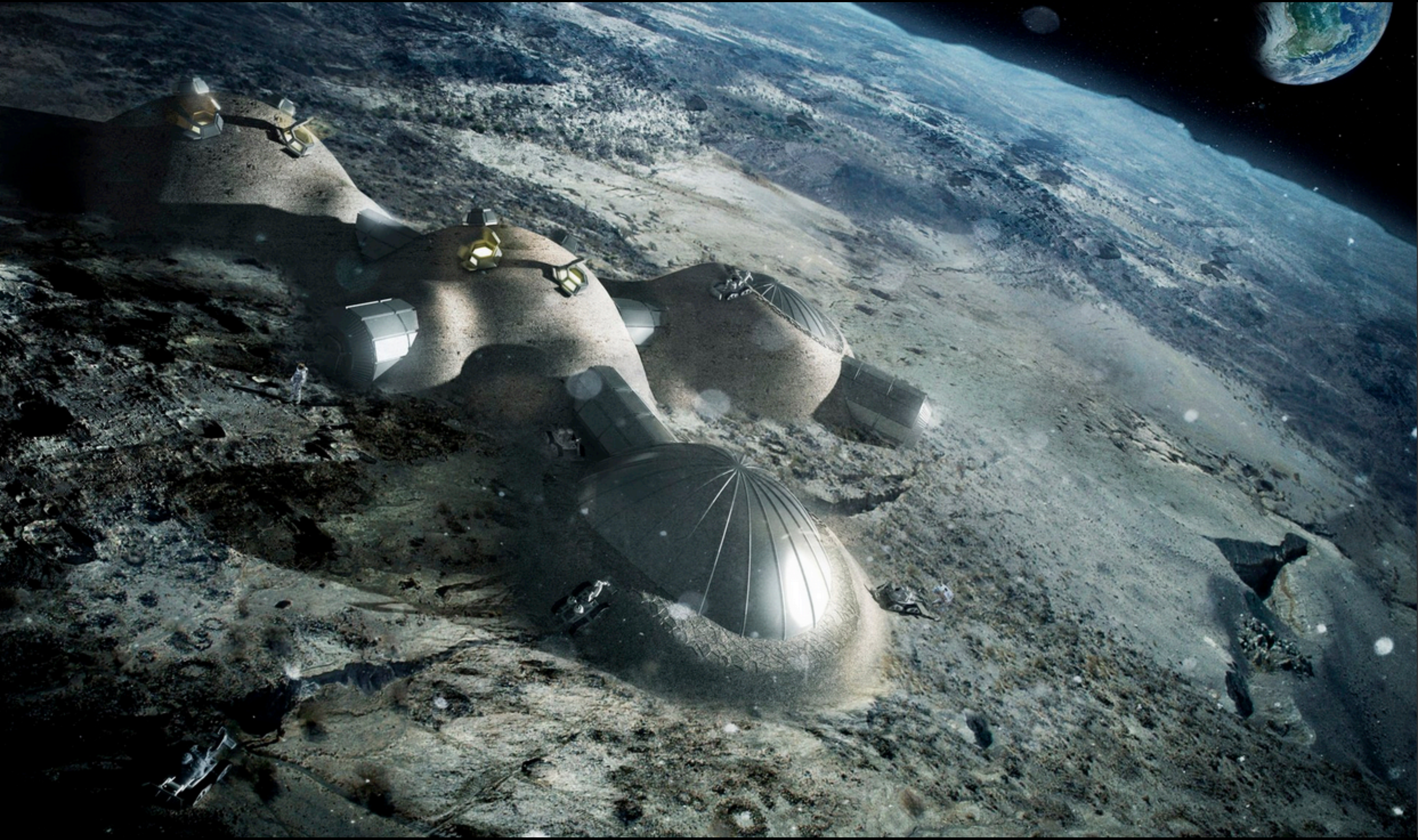


Shackleton crater



Thermal image

ESA concept: Moon Village

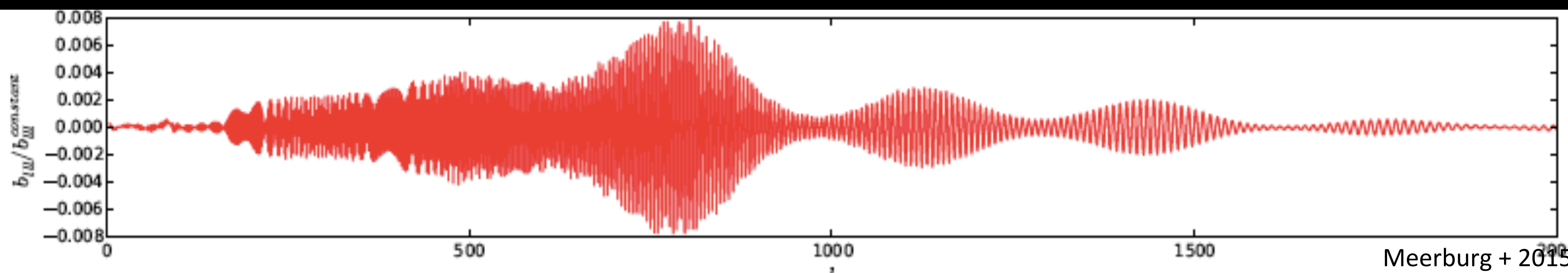


Aims: business and tourism in 2035+

A non-gaussianity program

f_{nl}~1 is a generic prediction in multifield inflation
aim: detect patterns of nongaussianity on the sky

- CMB: suborbital +space $N \sim 10^6$ $f_{nl} \sim 10$ ($>3\sigma$)
- Optical/IR galaxy surveys $N \sim 10^8$ $f_{nl} \sim 1$
- Radio: SKA-Low-2: $\sim 10^6$ antennae in 2025 (W. Australia)
- far side of Moon…$N \sim 10^{10}$ $f_{nl} \sim 0.1$ by 2035
- and eventually $N \sim 10^{12}$ $f_{nl} \sim 0.01$



Meerburg + 2015

conclusions

Nongaussianity is the ultimate probe of inflation
Observable via 21cm in dark ages: need many modes

Dark matter may be primordial black holes (PBH)
over broad mass range
PBH of ~10^3−10^5 M_{sun} can solve all dwarf galaxy “problems”

Forming PBH requires primordial nongaussianity

Lunar radio array will provide

- 100 improvement in precision cosmology
- by 2040 when Keith will still be young

thanks keith for great collaborations and interactions over 30 + years!

happy birthday!